Environmental dependence of halo formation times

Geraint Harker

Motivation

- Assumptions about the environmental dependence of halo formation times are implicit in semi-analytic models:
  - In merger trees based on extended Press-Schechter theory the distribution of formation redshifts is a function only of the mass of a halo, and not of its environment.
  - Even if not manifested in spatially-averaged quantities, the dependence could become important when considering e.g. clustering statistics.

Calculation of formation redshift

- Consider parent halos with 64 or more particles in the merger trees calculated by John Helly using the SubFind groups.
- Starting at the final snapshot, move back slice by slice, and at each stage:
  - Identify the 'main progenitor' as the most massive identified in the merger tree.
  - If this has mass less than half the mass of the parent halo, use the redshift of the previous snapshot as the formation redshift.
  - Otherwise, move to the next redshift slice, identifying the main progenitor there, and so on.
- This corresponds with the formation time as defined in e.g. the theoretical studies of Lacey & Cole (1993).

The Marked Correlation Function

- Described in Sheth & Tormen (2004), this is a generalisation of the two-point correlation function.
- For each halo, i, we define a 'mark' m_i. The mark may be, for example, the formation redshift. Then the marked correlation function, $M(r)$, is defined by

$$M(r) = \frac{\sum_{\{i,j\}} m_i m_j}{\sum_{\{i,j\}} \overline{m}^2}$$

  where the sum is taken over all pairs of objects $\{i,j\}$ with separation $r=r_{ij}$ but where the mean is taken over all objects in the sample.
- Therefore if $M(r)>1$ pairs of objects with separation r tend have a greater value of the mark than average.
- We do not need to choose a spatial scale to define environment – the marked correlation function picks this out for us.

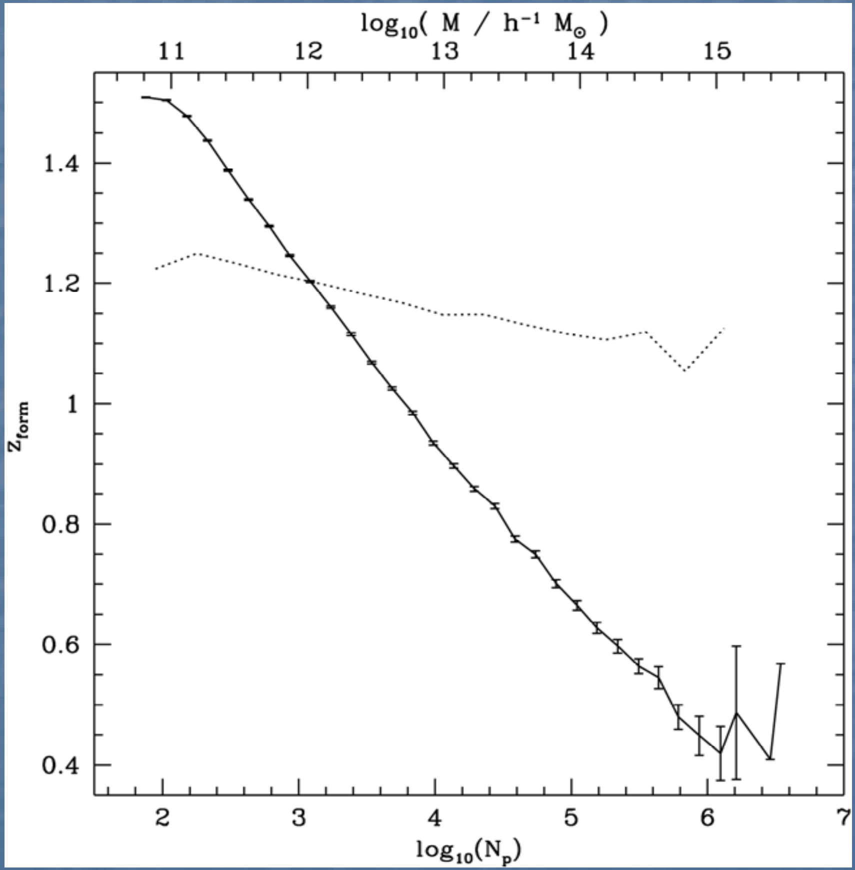
Scaled formation redshift

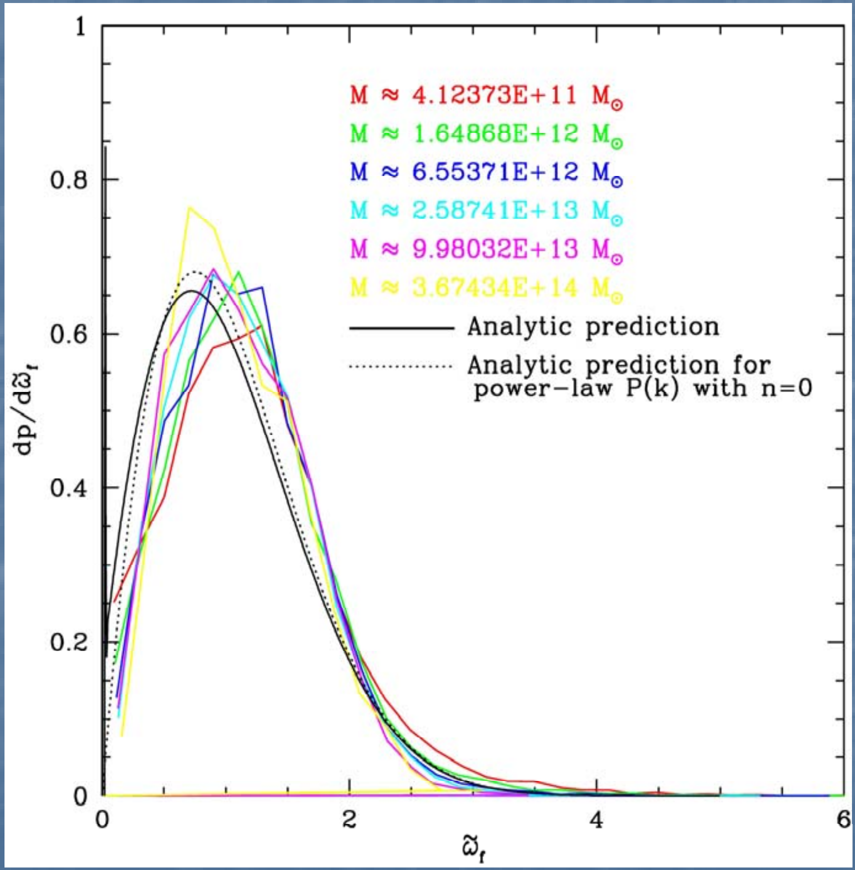
- Instead of raw formation redshift, we use the quantity $\tilde{\omega}$ defined in Lacey & Cole (1993) by:

$$\tilde{\omega} = \frac{\delta(z_{\mathrm{form}}) - \delta(0)}{\sqrt{\sigma^2(M/2) - \sigma^2(M)}}$$

- This precisely scales out the mass dependence of formation redshift in extended Press-Schechter theory for scale-free initial power spectra (and very nearly does otherwise).

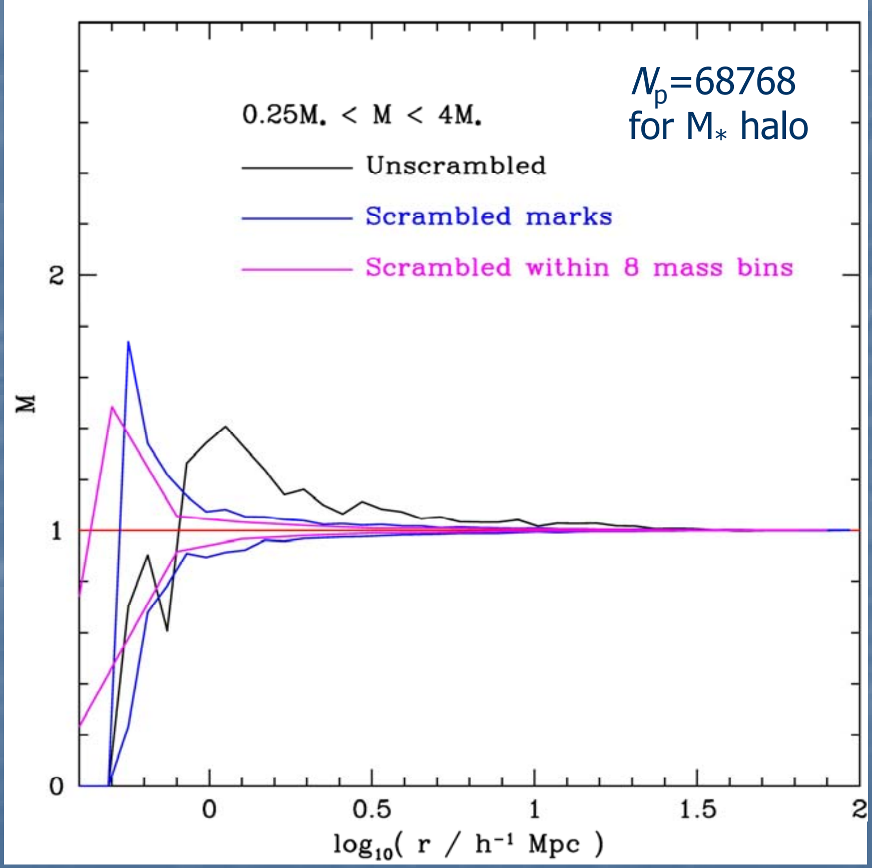
Scaling tests



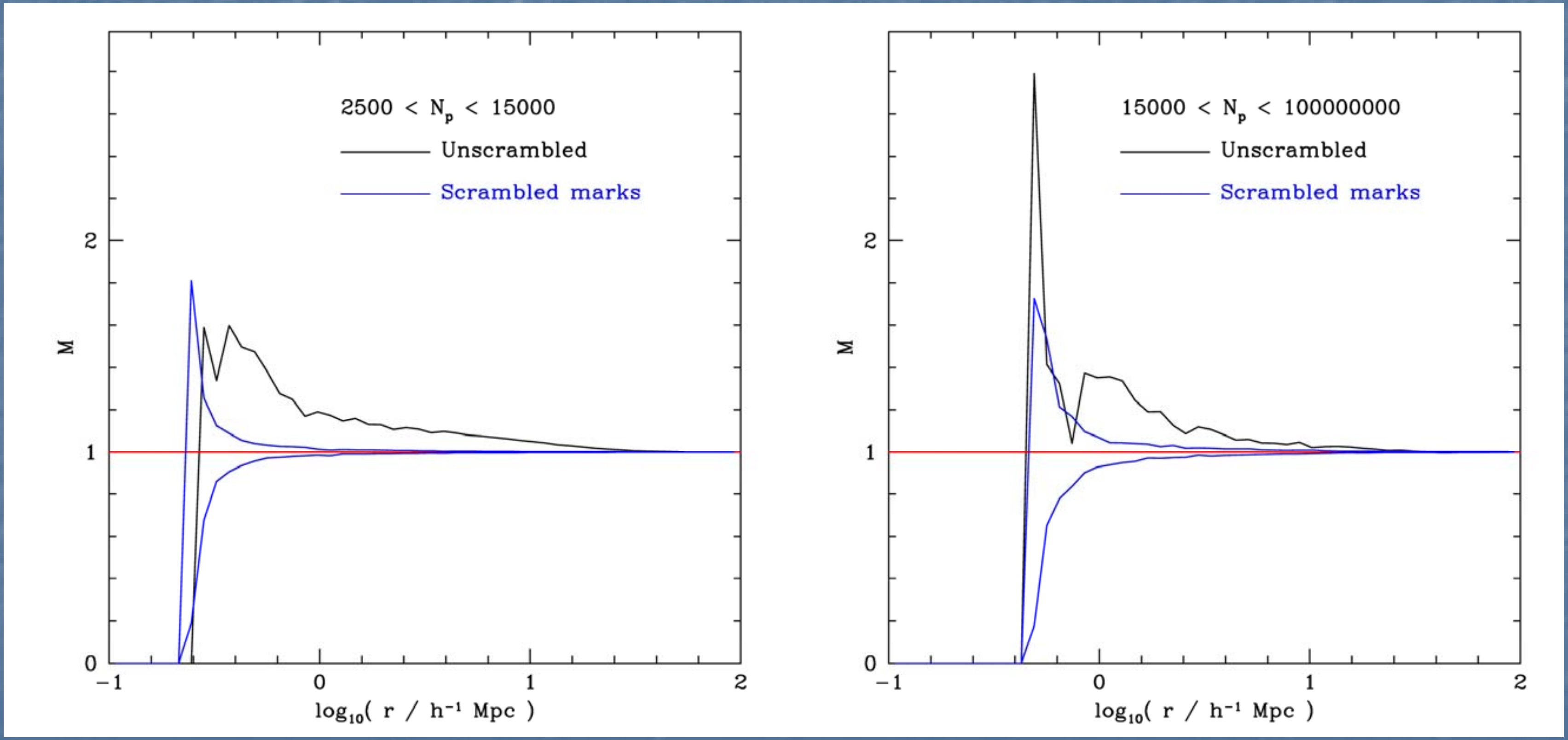


An example of a marked correlation function

- 'Scrambled' means we randomly permute the marks between the halos in the sample.
- Scrambling within mass bins implies we only permute the marks between halos of similar mass.
- These processes would be equivalent if the scaled formation redshift precisely scales out the mass dependence.



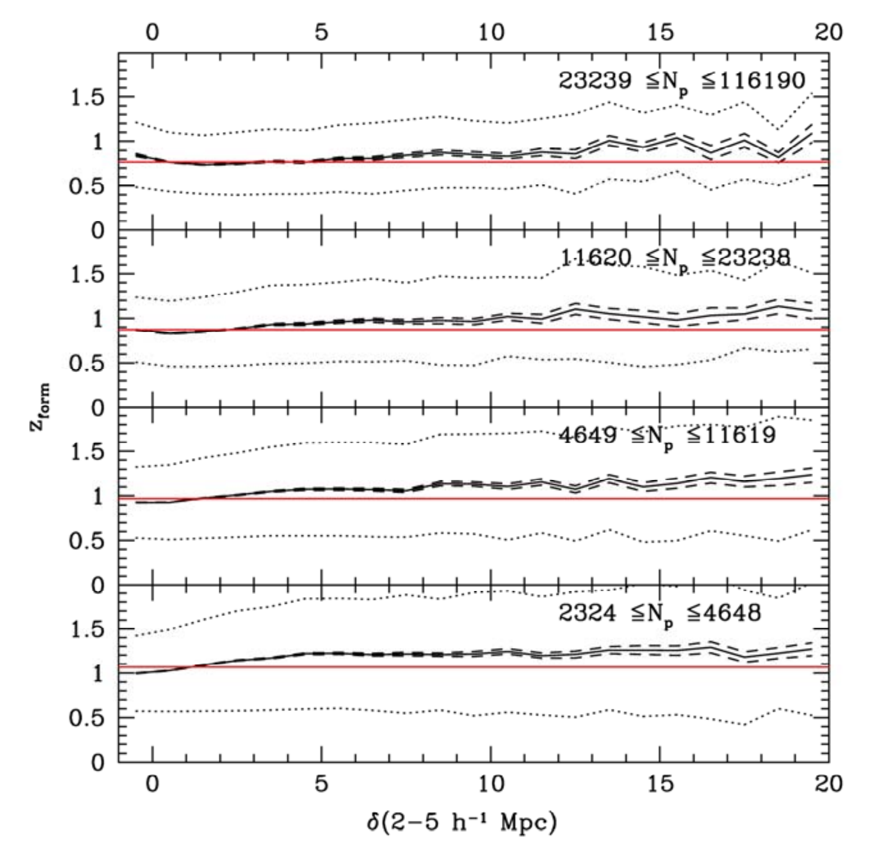
Different mass ranges



Other tests of environmental dependence

- Lemson & Kauffmann (1999) used as a measure of environment the overdensity within an annulus of

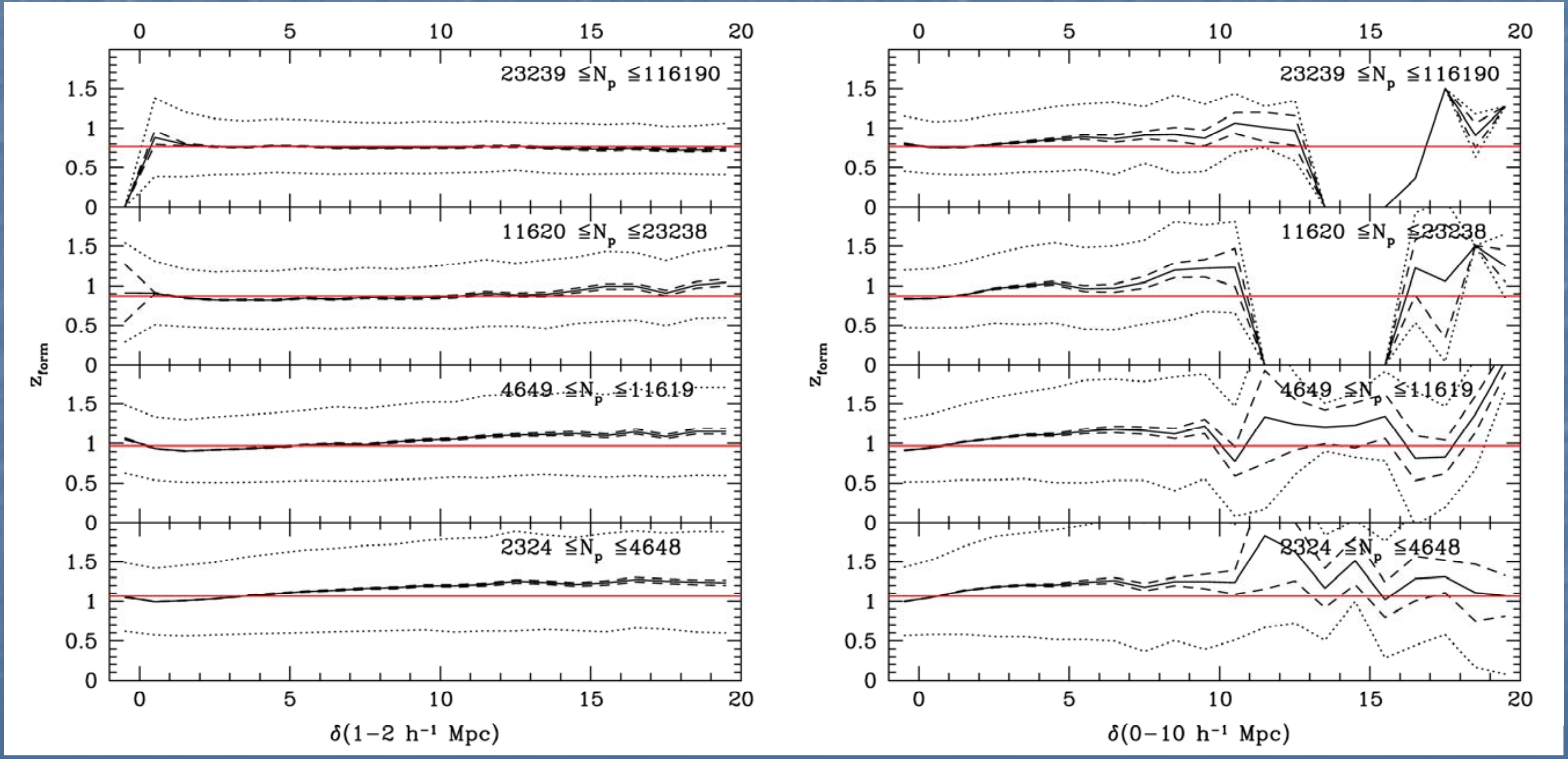
  2 < r / h^{-1}Mpc < 5 centred on the halo.
- They found no signal, but the better statistics available from the Millennium Simulation do suggest a dependence on environment.



Further work

- More experimentation with different mass ranges and comparison to traditional measures of environment.
- A marked cross-correlation function?
- Alternative marks: for example, the number of progenitors above a certain mass or different definitions of formation time.
- Effects of the above on clustering statistics, either of (sub)halos or semi-analytic galaxies.
- Further interpretation.
- Different redshifts.

Traditional tests of environment suggested by marked correlation function results



Further scaling tests

- Compare the marked correlation function with $\tilde{\omega}$ as the mark with the function when we:
  - Use raw formation redshifts;
  - Shuffle marks within small mass bins;
  - Scale formation redshifts by dividing through by the mean formation redshift of halos of the same mass in the simulation.
  - Rank the scaled formation redshifts then force them to follow the analytic distribution.
- The latter three make little difference to the final result.

Lemson & Kauffmann figure using scaled formation redshift